Intensification of the annual cycle in the tropical Pacific due to greenhouse warming

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[1] The annual cycle is one of the most important components of the global climate system Yet little attention has been paid to the response of the equatorial annual cycle to anthropogenic climate change. Here we present results from a global climate model with high tropical resolution that simulates a strong intensification of the annual cycle in the tropical Pacific in response to increased greenhouse gas concentrations. This sensitivity of the tropical annual cycle to greenhouse warming can be explained in terms of tropical ocean-atmosphere feedbacks. A possible amplification of the tropical annual cycle is expected to have also profound ecological and societal impacts. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Timmermann, A., F.-F. Jin, and M. Collins (2004), Intensification of the annual cycle in the tropical Pacific due to greenhouse warming, *Geophys. Res. Lett.*, *31*, L12208, doi:10.1029/2004GL019442.

1. Introduction

[2] Although the sun crosses the equator twice yearly, the tropical eastern and central Pacific climate system exhibits a pronounced annual rather than a semi-annual cycle [*Xie*, 1994]. One of the key prerequisites for the equatorial annual cycle is the northern position of the Intertropical convergence zone (ITCZ) that is partly controlled by the existing land-sea contrasts in the eastern equatorial Pacific area [*Philander et al.*, 1996]. This hemispheric asymmetry is responsible for a weak annual cycle surface wind forcing on the equator [*Li and Philander*, 1996]. In addition, coupled air-interactions [*Philander et al.*, 1996; *Li and Philander*, 1996; *Xie*, 1996] generate a westward-propagating equatorial mode with near-annual frequency that intensifies the annual wind forcing.

[3] This positive feedback leads to the establishment of a coupled annual cycle in the eastern and central equatorial Pacific. Due to this positive feedback the tropical annual cycle is interacting with the El Niño-Southern Oscillation (ENSO) phenomenon [*Xie*, 1995] as well as with an anticipated greenhouse warming. So far the sensitivity of the tropical annual cycle to anthropogenic climate change has not been addressed in otherwise thorough assessments of climate change [*IPCC*, 2001].

[4] In order to study the effect of greenhouse warming on the equatorial annual cycle we analyze a control and a greenhouse warming simulation performed with the coupled general circulation model (CGCM) ECHAM4/OPYC.3 that has been used in previous global change studies [*Timmermann et al.*, 1999; *Hu et al.*, 2000; *Latif et al.*, 2000; *Hegerl et al.*, 2000; *Roeckner et al.*, 1999]. This model uses a meridional resolution in the tropical ocean of 0.5 degree, sufficient to resolve equatorial planetary waves in the ocean. A recent assessment [*Achutarao and Sperber*, 2002] of CGCMs revealed that climate models that are not constrained by the use of an annually-varying flux correction still have fundamental difficulties in simulating the tropical annual cycle realistically. The strength of our simulated sea surface temperature (SST) annual cycle in the eastern equatorial Pacific (Figure 1) is somewhat weaker (30%) than in the observations (not shown). In both, model and observations, a clear westward propagation of the SST pattern can be seen (Figure 1, left panel), that is attributable to coupled air-sea interactions.

2. Annual Cycle Changes in the Tropical Pacific Ocean

[5] Here we focus on a transient greenhouse warming simulation conducted with ECHAM4/OPYC.3. The model was forced by increasing levels of greenhouse gas concentrations as observed (1860–1990) and according to the IPCC scenario IS92a (1990–2100). The Pacific warming pattern (Figure 2) is characterized by an eastern equatorial Pacific warming due to coupled dynamics [*Jin et al.*, 2001] and a significant hemispheric warming asymmetry. In addition to these mean climate changes in the Pacific, the ECHAM4/OPYC.3 CGCM simulation predicts an increase of ENSO activity [*Timmermann et al.*, 1999] for the 21st century as well as an enhanced asian summer monsoon [*Hu et al.*, 2000]. Figure 1 (right panel) shows that the annual cycle of sea surface temperatures in the equatorial Pacific undergoes significant changes due to anthropogenic greenhouse warming. The anomalous equatorial annual cycle (with the mean SST pattern removed) is comparable in

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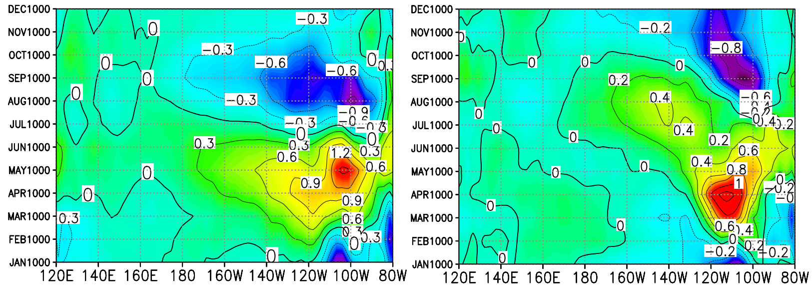

Figure 1. Left: Simulated annual cycle of sea surface temperature [K] using the ECHAM4/OPYC.3 present-day simulation. Right: Simulated difference of the annual cycle of sea surface temperature [K] between the periods 2060–2100 and 1860–1900.

magnitude with the mean annual cycle in the tropical Pacific without greenhouse perturbations. The range of the unperturbed annual cycle in eastern equatorial Pacific SST amounts to about 1.8°C. Hence, the CGCM simulates almost a doubling of the annual cycle amplitude in response to anthropogenic climate change (Figure 1, right panel). Apparently the seasonal cycle changes in high latitudes (not shown) are very much different exhibiting a reduction of the annual temperature range due to the snow/albedo feedbacks and reductions in soil moisture as described in *Manabe et al.* [1992]. The origin of the annual cycle intensification in the tropical Pacific can be traced back to the asymmetric meridional temperature response in the Pacific area (see Figure 2), that is mainly due the hemispheric differences in land mass distributions. Owing to the different heat capacities of land and ocean a rather robust warming pattern can be anticipated that is characterized by a strong northern hemispheric and a moderate southern hemispheric warming. This asymmetric warming changes also the tropical temperatures via forcing of the tropical asymmetric mode [*Xie*, 1996]. In Figure 2 we observe strong southeasterly trade wind anomalies in the southern hemisphere which will enhance the wind-evaporation feedback, thereby damping the local warming tendency due to longwave radiation. In total the equatorial meridional wind anomalies are strongly dominated by a southern hemispheric component. This has strong implications for the strength of the annual cycle as pointed out by *Xie* [1996] for present-day climate conditions. The zonal wind trend on the equator is mostly driven by the atmospheric response to the enhanced warming in the eastern equatorial Pacific [*Jin et al.*, 2001].

[6] An important component in understanding the annual cycle intensification is the thermal and dynamic oceanic response to a secular increase of the meridional wind component near the equator. The relevant variables are the mixed layer temperature T, the 3-dimensional ocean current vector **V** and the net heat flux Q. These variables are decomposed into a climatological mean state (denoted by a bar) and its annual cycle component without greenhouse forcing (subscript ca), an anomalous time mean (bared quantity with subscript w) and an anomalous annual cycle term (subscript a) due to greenhouse forcing:

$$T = \overline{T} + T_{ca} + \delta T_w + \delta T_a \quad (1)$$

$$\mathbf{V} = \overline{\mathbf{V}} + \mathbf{V}_{ca} + \delta \mathbf{V}_w + \delta \mathbf{V}_a \quad (2)$$

The linearized SST equation for the anomalous annual cycle becomes

$$\frac{\partial \delta T_a}{\partial t} = -\overline{\mathbf{V}} \nabla \delta T_a - \delta \mathbf{V}_a \nabla \overline{T} - \mathbf{V}_{ca} \nabla \delta T_w - \delta \mathbf{V}_w \nabla T_{ca} + \delta Q_a \quad (3)$$

$$= A + B + C + D + \delta Q_a = L(\delta T_a) + F_a, \quad (4)$$

where

$$L(\delta T_a) = -\overline{\mathbf{V}} \nabla \delta T_a - \delta \mathbf{V}_a \nabla \overline{T} + \delta Q_a \quad (5)$$

$$F_a = -\mathbf{V}_{ca} \nabla \delta T_w - \delta \mathbf{V}_w \nabla T_{ca}. \quad (6)$$

The anomalous annual cycle of surface heat flux is mostly governed by changes of the solar radiation due to cloud shielding and latent heat flux anomalies, as can be seen from Figure 3. Both contributions originate directly from the atmospheric dynamical response [*Gill*, 1980] to the anomalous annual cycle of SST (Figure 1, right panel). Cloud shielding is a negative feedback. Based on the comparison between Figure 1 (right panel) and Figure 3 (right panel) cloud shielding can be parameterized in terms of a linear damping $-\epsilon \delta T_a$ term. The positive wind-evaporation feedback due to the local [*Gill*, 1980] wind response is shown in Figure 3 (left panel). Symbolically the wind-evaporation feedback is expressed as a linear operator $E(\delta T_a)$. Thus, we obtain $\delta Q_a = -\epsilon \delta T_a + E(\delta T_a)$. $L(\delta T_a) = A + B + \delta Q_a$ represents a linear coupled operator that quantifies the effect of δT_a on the winds and the wind effect on

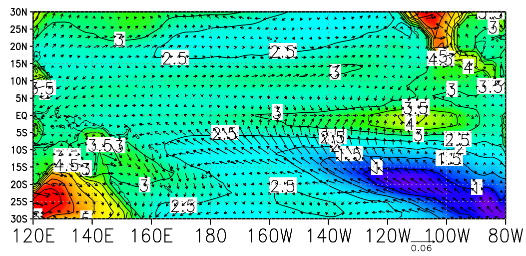

Figure 2. Simulated time-mean difference of sea (land) surface temperature [°C] and difference of wind stress vectors [Pa] between the periods 2060–2100 and 1860–1900.

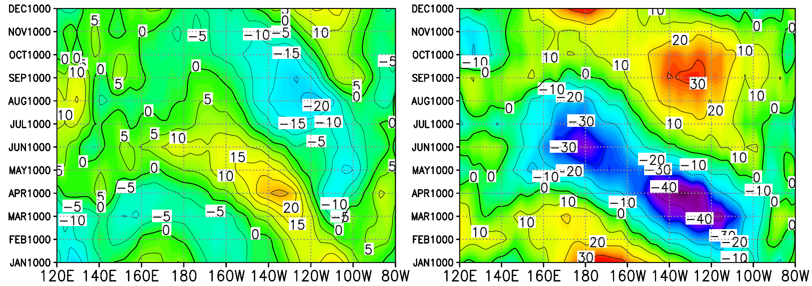

Figure 3. Left: Simulated difference of the annual cycle of latent heating [W/m^2] between the periods 2060–2100 and 1860–1900. Right: Same as left but for the surface solar radiation.

anomalous temperature advection and hence on the time derivative of δT_a. The forcing term F_a represents the dynamical heating that is generated by changes in the time mean state (δT_w, $\delta \mathbf{V}_w$) of the tropical Pacific due to greenhouse warming. It can be decomposed into the terms C, D representing the climatological advection of the anomalous time mean temperature and the anomalous time mean advection of climatological temperature, respectively. Nonlinear terms have been neglected. The time evolution of A, B, C, D along the equator is depicted in Figure 4. The most important contribution for $\dot{\delta T_a}$ is due to B, as part of the linear coupled operator $L(\delta T_a)$, which directly forces the westward propagating anomalous annual cycle in SST similar to the present-day situation [*Xie*, 1996]. The westward propagation of the anomalous annual cycle due to the coupled dynamical operators $L(\delta T_a)$ and in particular $E(\delta T_a)$ can be explained as follows: A positive temperature anomaly creates a Gill-type atmospheric response [*Gill*, 1980] that is associated with a reduction of the equatorial trades to the west of the anomaly and an intensification to the east of it (see Figure 1 (right), December/March). The trade wind reduction decreases latent cooling (Figure 3, left panel) as was well as Ekman upwelling, eastward advection of cold waters (Figure 4, upper right) and oceanic mixing. The result is a westward extension of the SST. The reverse happens on the eastern side of the SST anomaly (as can be seen from Figure 1 right, June/September). The resulting westward propagating coupled instability is responsible for the generation of the annual cycle and the amplification of the anomalous annual cycle in the equatorial Pacific. Furthermore, D (see Figure 4, lower right panel) provides a seeding for the anomalous SST annual cycle (Figure 1, right). The seeding is particularly strong near 110°W and a clear phase difference can be seen between F_a (Figure 4) and δT_a (Figure 1, right) of about 3 months, illustrating that $F_a = C + D$ is a major component in forcing the anomalous annual cycle in SST. Hence, the greenhouse perturbation F_a introduces an additional forcing to the coupled operator L, thereby intensifying the annual cycle.

3. Discussion and Summary

[7] The physical chain reactions for the amplification of the annual cycle due to greenhouse warming are summarized in Figure 5: The asymmetric greenhouse warming pattern induces current changes $\delta \mathbf{V}_w$, which in turn lead to the initial generation of the anomalous annual cycle of SST. In turn coupled instabilities due to the wind evaporation feedback (Figure 3, left) and anomalous annual cycle current changes (Figure 4, upper right) lead to an amplification of δT_a. This amplification is leveled off by the cloud shielding effect (Figure 3, right) which leads to local damping of δT_a.

[8] In the recent Third Assessment Report of the International Panel on Climate Change [*IPCC*, 2001], evidence is presented that spring temperatures in the tropical Pacific have become warmer than autumn temperatures during the period from 1976–2000. This trend pattern in the seasonal cycle reflects also an intensification of the annual cycle, consistent with our modeling results. However, it should be noted that the strength of the seasonal cycle in the tropical Pacific has also undergone significant interdecadal changes throughout the last 100 years [*Gu and Philander*, 1995]. As to whether the recent trend in the tropical annual cycle in SST is due to greenhouse warming is an open question and requires a more thorough statistical assessment using e.g., optimal fingerprinting techniques.

[9] Projected changes in the strength of the tropical annual cycle are expected to have important influences on marine and terrestrial ecological systems, and hence also on human societies. Growing seasons of plants, and hence

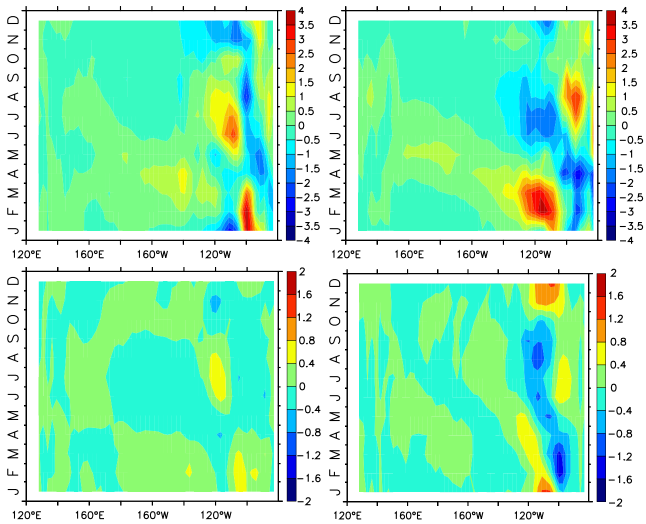

Figure 4. Upper left: The anomalous annual cycle of mean advection of anomalous annual cycle temperature (a); Upper right: Anomalous annual cycle advection of the mean temperature (b); Lower left: Climatological advection of the anomalous time mean temperature (c); Lower right: Anomalous time mean advection of climatological temperature. (d) Units are °C/month.

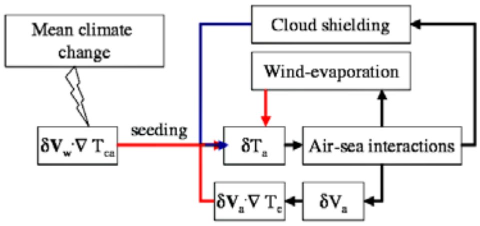

Figure 5. Schematics representing the most dominant feedbacks that are responsible for the intensification of the annual cycle. Blue and red arrows denote negative and positive feedbacks for δT_a, respectively.

crops, as well as of marine organisms might change significantly in response to a possible doubling of the annual cycle strength in the tropical Pacific. There is also compelling evidence for an interaction between the tropical annual cycle and ENSO [*Jin et al.*, 1994; *Tziperman et al.*, 1994]. ENSO irregularity as well as the variance enhancement during the boreal winter season have been attributed to interactions among seasonal and interannual variability.

[10] Much further work is needed to clarify the role of these interactions both for a present-day and future greenhouse warming climate using other CGCMs. Initial assessment of those models submitted to the CMIP2 project (http://www-pcmdi.llnl.gov/cmip) show a large range of responses with some models showing an increase in the amplitude of the annual cycle, some showing no change, and some even showing a decrease in amplitude. Resolving these model-uncertainties should be a key issue for future climate change assessments.

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